The Status of GMSB after 1/fb at the LHC

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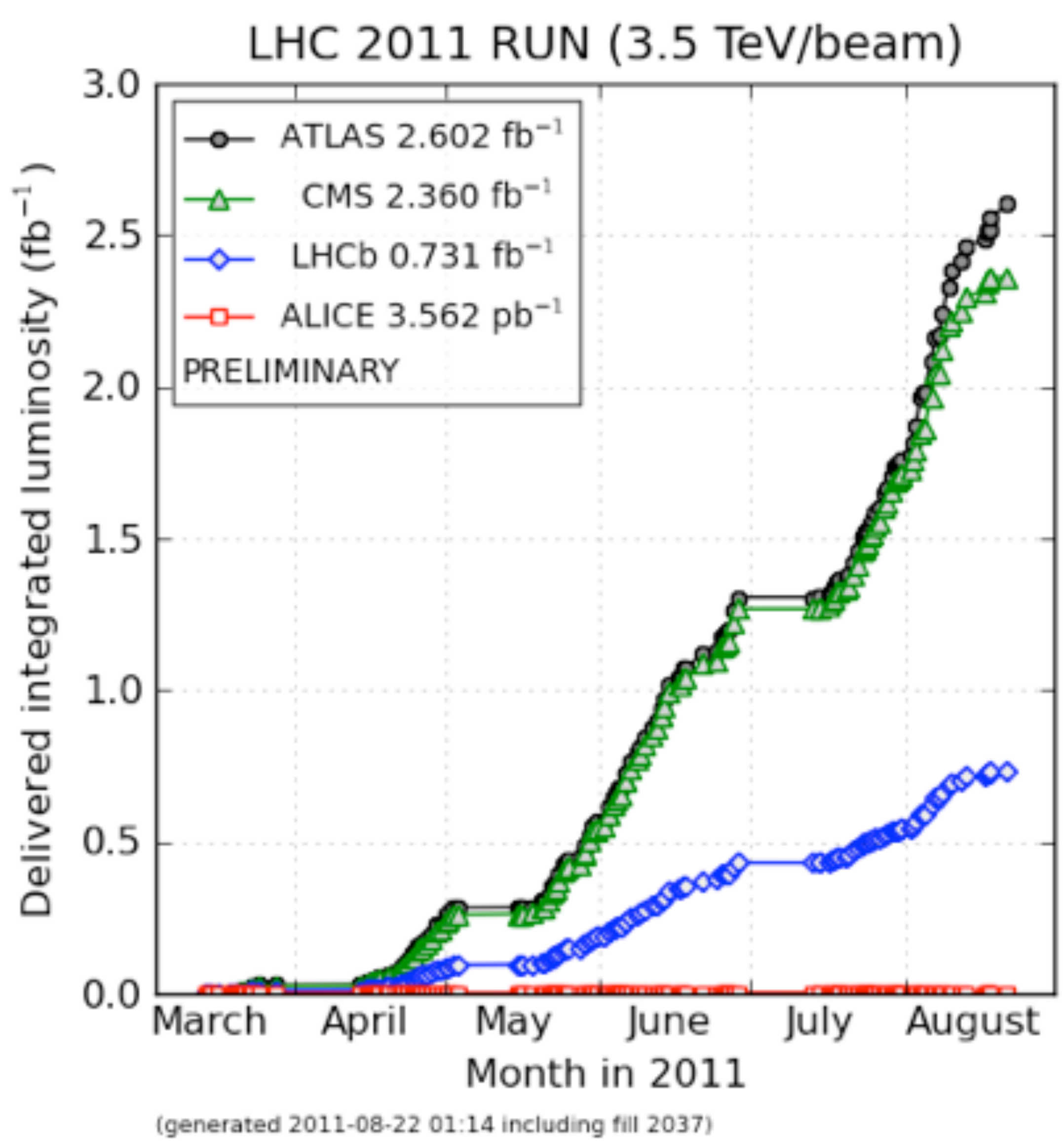
Work in progress with Yevgeny Kats, Patrick Meade, and Matt Reece

Also based on:

Meade, Reece & DS (0911.4130, 1006.4575)
Ruderman & DS (1009.1665, 1103.6083)
Kats & DS (1106.0030)

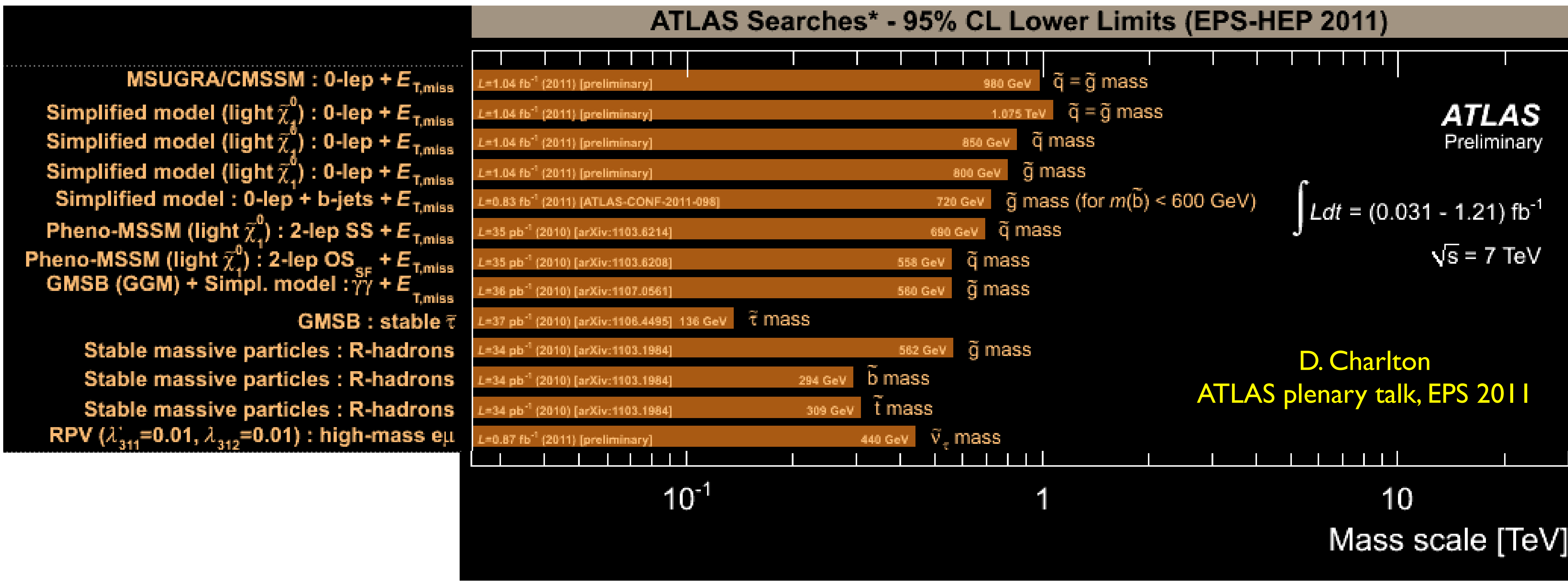
Current Status of the LHC

In 2011, the LHC experiments have been collecting data at an astounding rate -- over 2/fb already and growing!



Current Status of the LHC

So far, no signs of supersymmetry...



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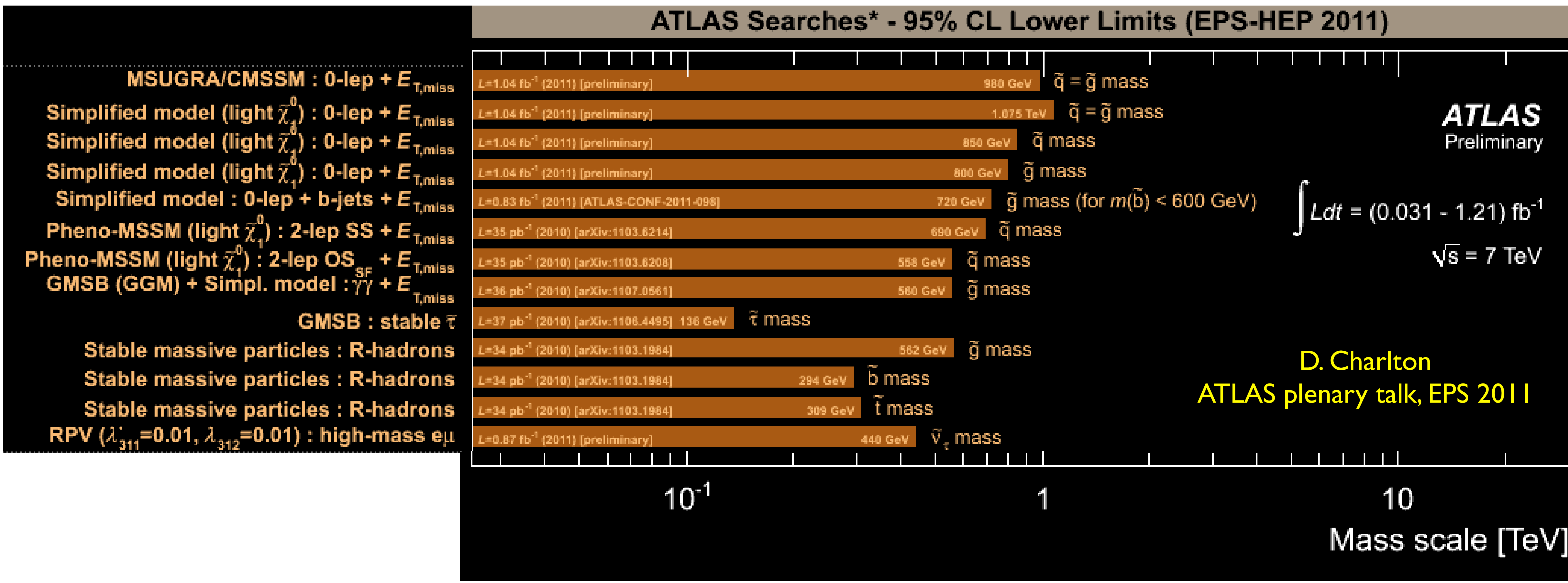

Should we be concerned???

Today’s Talk

- In today’s talk, I will take you on a guided tour of the latest SUSY searches from the LHC.
- We will focus on their implications for model-independent low-scale SUSY-breaking scenarios (general gauge mediation).
- As we’ll see, studying signatures of GGM naturally leads one to consider most (all?) of the LHC SUSY searches
  -- GGM as a “signature generating machine”
- GGM provides a nice unifying framework with which to understand all the different LHC results!

Today's Talk

- In today's talk, I will take you on a guided tour of the latest SUSY searches from the LHC.
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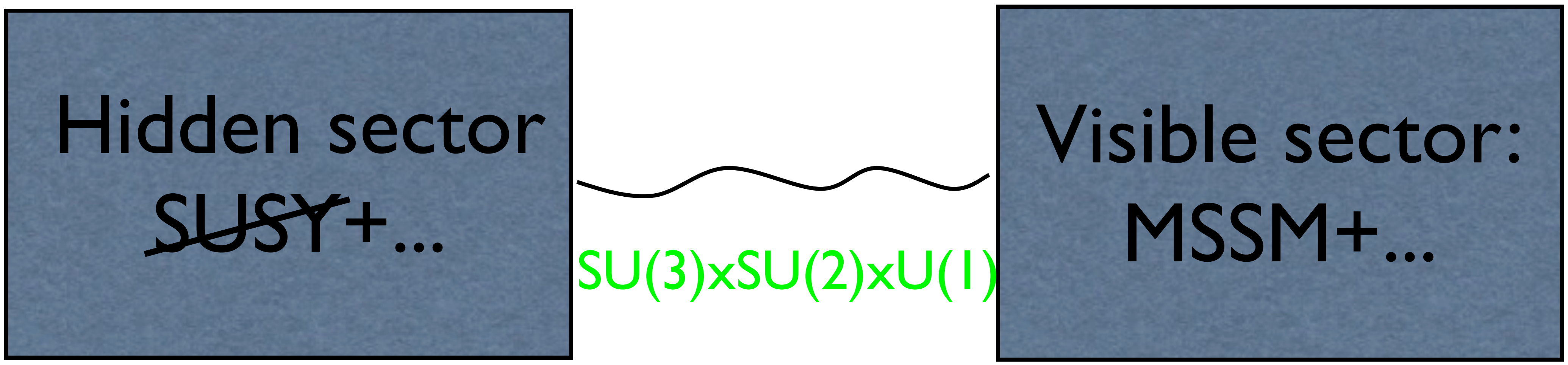
- As we'll see, studying signatures of GGM naturally leads one to consider most (all?) of the LHC SUSY searches
  -- GGM as a "signature generating machine"
- GGM provides a nice unifying framework with which to understand all the different LHC results!

Rumors of SUSY's demise are greatly exaggerated.

Gauge Mediation



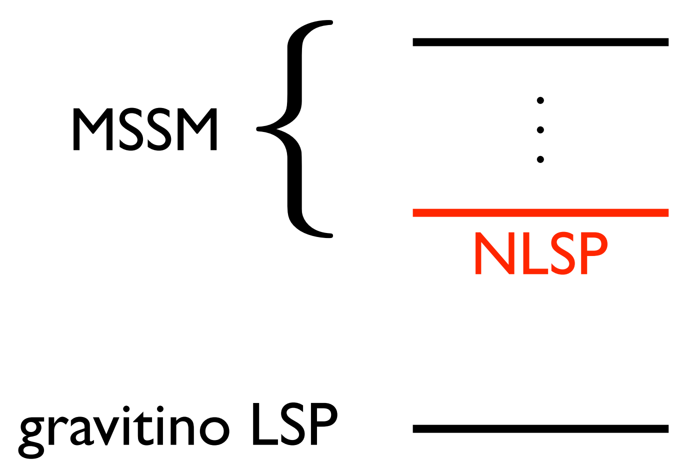
- Gauge mediation is a very attractive scenario for the MSSM:
  - Solves SUSY flavor problem
  - Calculable framework
- Recently, a model-independent framework for GMSB was formulated, and the full parameter space was understood:
- "General Gauge Mediation" (Meade, Seiberg & DS; Buican, Meade, Seiberg & DS)
- LHC searches are now being designed with GGM in mind!

The NLSP

- Gravitino LSP is a universal prediction of gauge mediation models:

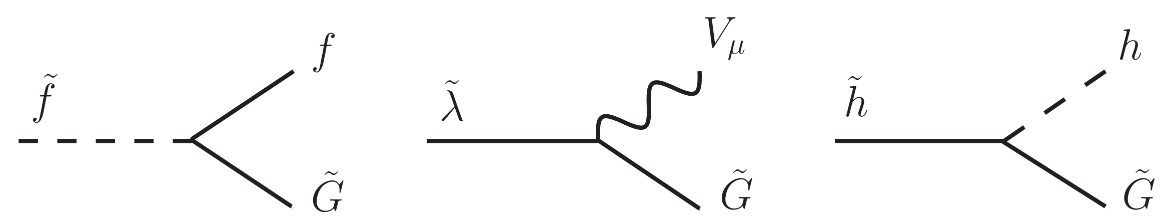
$$m_{3/2} = \frac{F}{\sqrt{3}M_{pl}} \quad (\sim \mathrm{eV} - \mathrm{GeV})$$

- Lightest MSSM sparticle becomes the next-to-lightest superpartner (NLSP).



NLSP Collider Signatures

- In gauge mediation, the NLSP type largely determines the inclusive collider signatures.
  - NLSP decays to the gravitino plus its SM partner.



  - Decays can be prompt or delayed: $\tau_{NLSP} \sim \frac{F^2}{m_{NLSP}^5}$
  - All SUSY cascade decays pass through the NLSP.
  - So all events contain:
    - high pT objects determined by the NLSP type
    - missing energy

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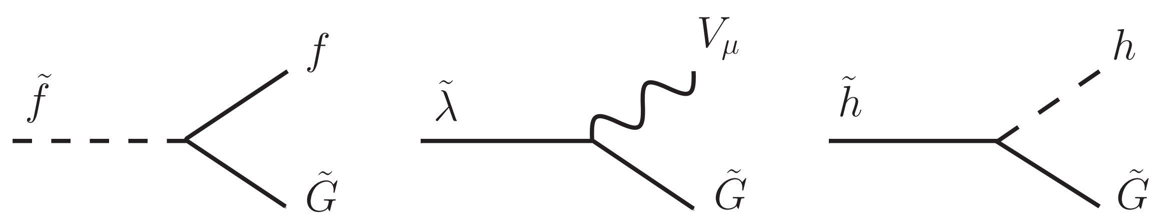


    - Decays can be prompt or delayed: $\tau_{NLSP} \sim \frac{F^2}{m_{NLSP}^5}$
    - All SUSY cascade decays pass through the NLSP.
    - So all events contain:
        - high pT objects determined by the NLSP type
        - missing energy

Will focus on prompt case today, to make contact with the bulk of the LHC SUSY searches.

NLSP Collider Signatures

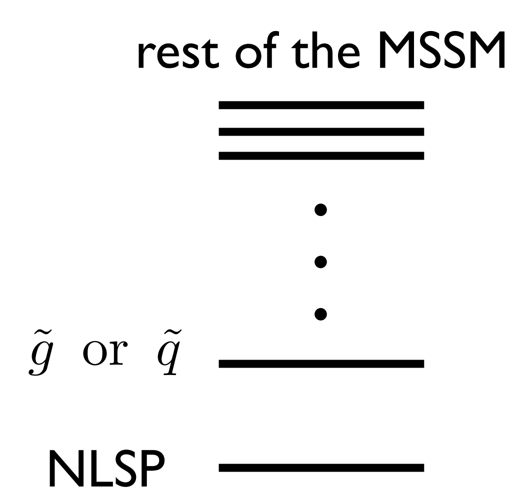
Names	spin 1/2	spin 1
gluino, gluon	$\widetilde{g}$	g
winos, W bosons	$\widetilde{W}^{\pm} \quad \widetilde{W}^0$	$W^{\pm} \quad W^0$
bino, B boson	$\widetilde{B}^0$	B^0

Names		spin 0	spin 1/2
squarks, quarks	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$
($\times$3 families)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$
sleptons, leptons	L	$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \quad e_L)$
($\times$3 families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$
Higgs, higgsinos	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$
	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$

- NLSP can be (almost) anything in the MSSM
  - neutralino (bino, wino, Higgsinos)
  - slepton (right-handed slepton, sneutrino)
  - gluino, squark (1st/2nd generation)
  - sbottoms, stops
- By considering all possible NLSP decays, can obtain a huge number of different final states!

The rest of the talk

- In the rest of the talk, I will give a quick overview of the current LHC searches, as seen through the lens of GGM.
- Our modus operandi:
    - Simulate signal events using public codes for spectrum generation (SoftSUSY and SDECAY), process generation (Pythia), jet clustering (FastJet), and NLO cross sections (Prospino).
    - Filter through homemade detector simulation (basic geometric acceptance, lepton isolation).
    - Validate on benchmark model points / grids provided by public experimental references.
    - Using experimentally-estimated backgrounds, derive limits on "simplified" GMSB scenarios (minimal spectra for production and decay).



Our Checklist

SUSY searches

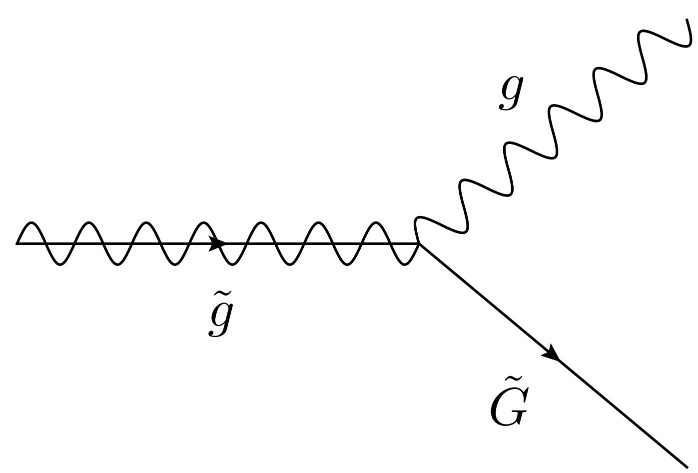
- Hadronic:
  - jets+MET
  - b-jets+MET
- Leptons:
  - lepton+jets+MET
  - Z+jets+MET
  - SS dilepton+MET
  - multileptons+MET
- Photons:
  - diphoton+MET
  - lepton+photon+MET
  - photon+jets+MET

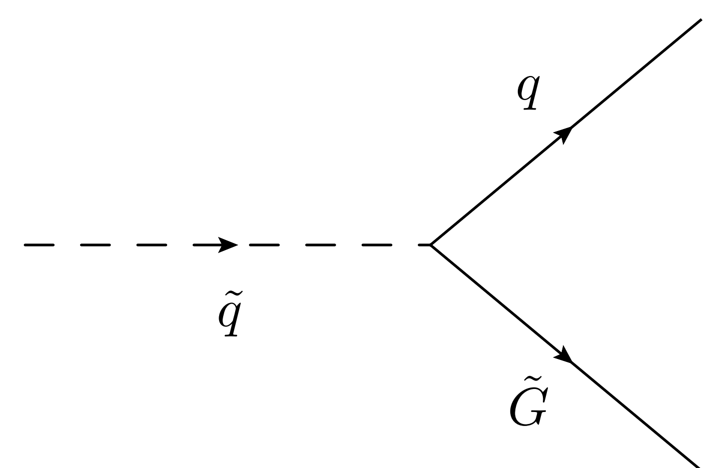
NLSP types

- gluino
- squark
  - 1st/2nd generation
  - sbottom
  - stop
- neutralino
  - bino
  - Higgsino (Z-rich)
  - Higgsino (h-rich)
  - wino
- slepton
  - flavor democratic
  - tau rich

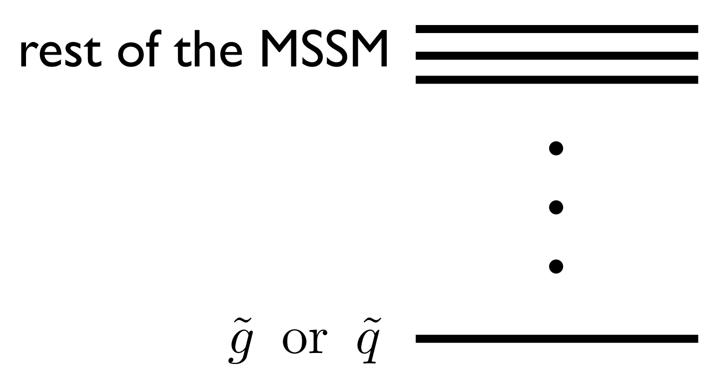
Gluino/Squark NLSP

- Decays directly to quark+gravitino and gluon+gravitino





- Rest of the spectrum becomes irrelevant. Can set limits on NLSP mass directly.

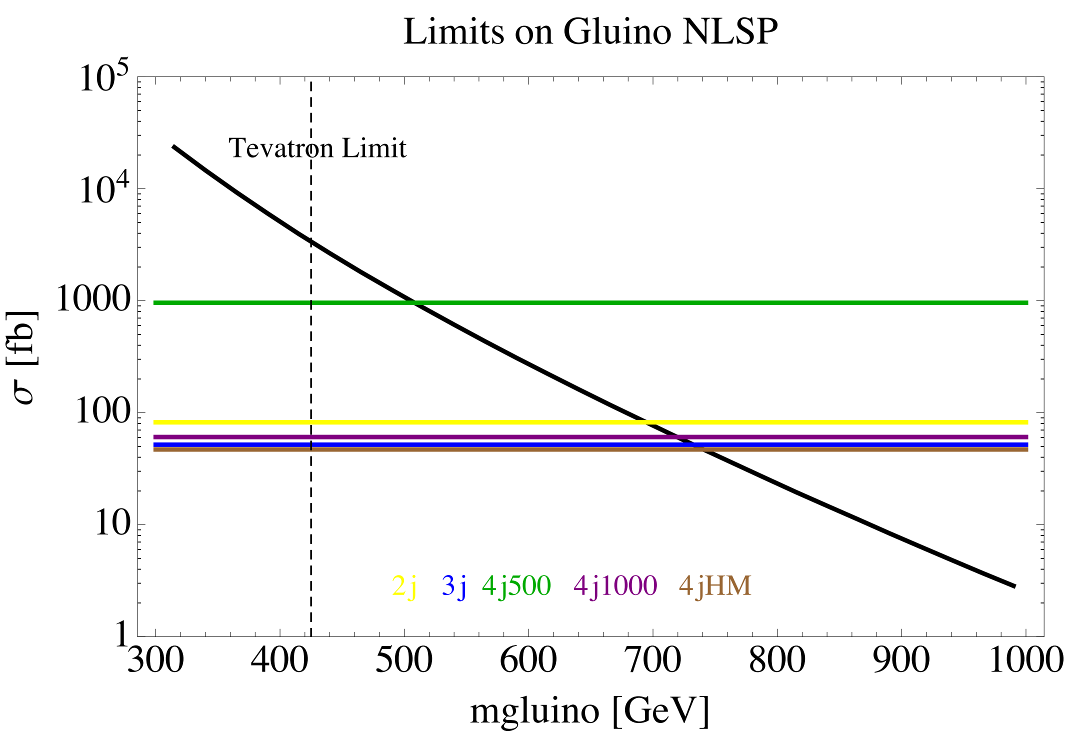


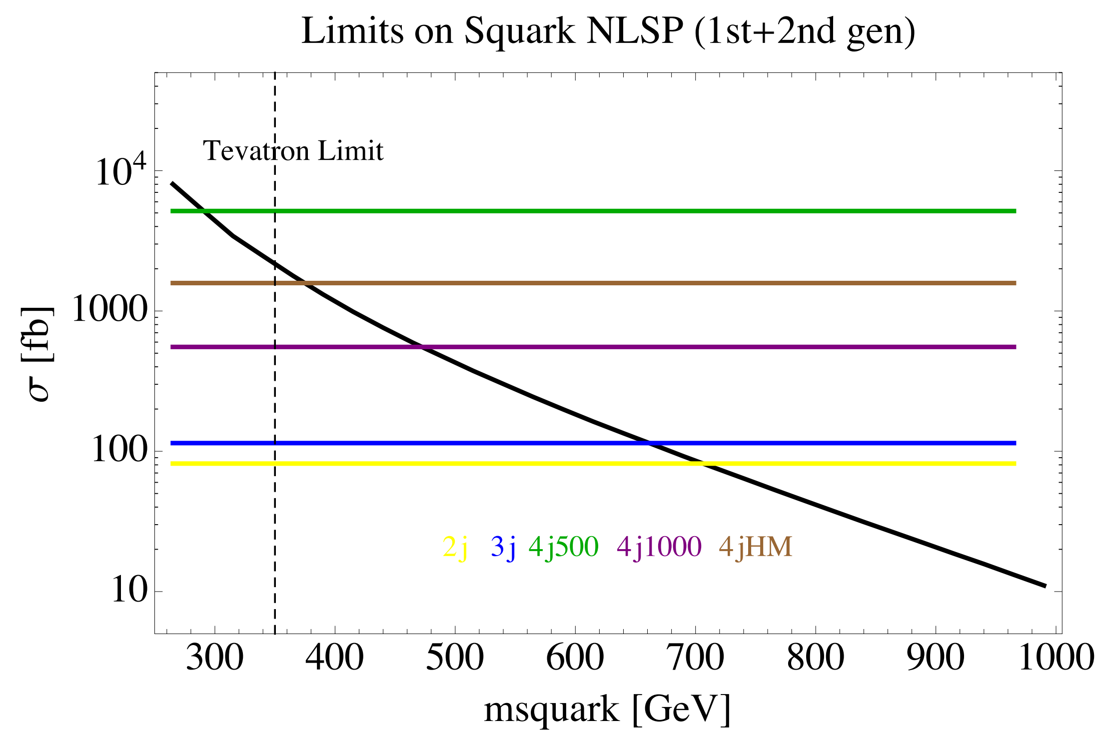
Gluino/Squark NLSP

- jets+MET is the granddaddy of all SUSY searches.
- It constrains GMSB with squark/gluino NLSP, and GMSB with colored production more generally.
- Latest search with 1/fb by ATLAS (I. Vivarelli, EPS 2011 talk)

Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, $m_{\mathrm{eff}} > 500$ GeV	$\geq$ 4-jet, $m_{\mathrm{eff}} > 1000$ GeV	High mass
Z/γ+jets	$32.5 \pm 2.6 \pm 6.8$	$25.8 \pm 2.6 \pm 4.9$	$208 \pm 9 \pm 37$	$16.2 \pm 2.1 \pm 3.6$	$3.3 \pm 1.0 \pm 1.3$
W+jets	$26.2 \pm 3.9 \pm 6.7$	$22.7 \pm 3.5 \pm 5.8$	$367 \pm 30 \pm 126$	$12.7 \pm 2.1 \pm 4.7$	$2.2 \pm 0.9 \pm 1.2$
$t\bar{t}$+ single top	$3.4 \pm 1.5 \pm 1.6$	$5.6 \pm 2.0 \pm 2.2$	$375 \pm 37 \pm 74$	$3.7 \pm 1.2 \pm 2.0$	$5.6 \pm 1.7 \pm 2.1$
QCD jets	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.74 \pm 0.14 \pm 0.51$	$2.10 \pm 0.37 \pm 0.83$
Total	$62.3 \pm 4.3 \pm 9.2$	$55 \pm 3.8 \pm 7.3$	$984 \pm 39 \pm 145$	$33.4 \pm 2.9 \pm 6.3$	$13.2 \pm 1.9 \pm 2.6$
Data	58	59	1118	40	18

Gluino/Squark NLSP





- Comments:
  - Interesting diffs between gluino & squark NLSP due to g vs q fragmentation
  - Nevertheless, best limits are comparable: m_{NLSP} > 700 GeV
  - Nature is probably not a promptly-decaying gluino or squark NLSP!

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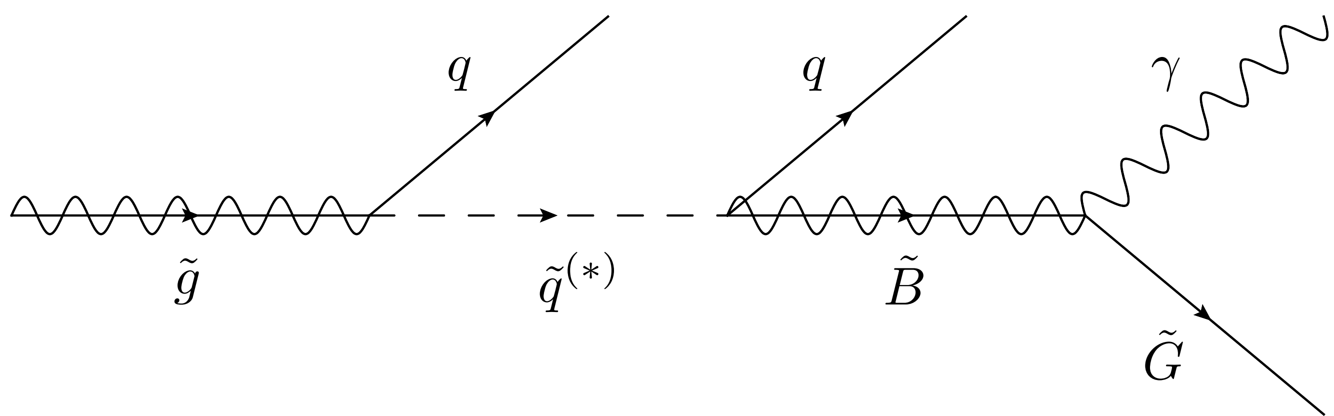
NLSP types

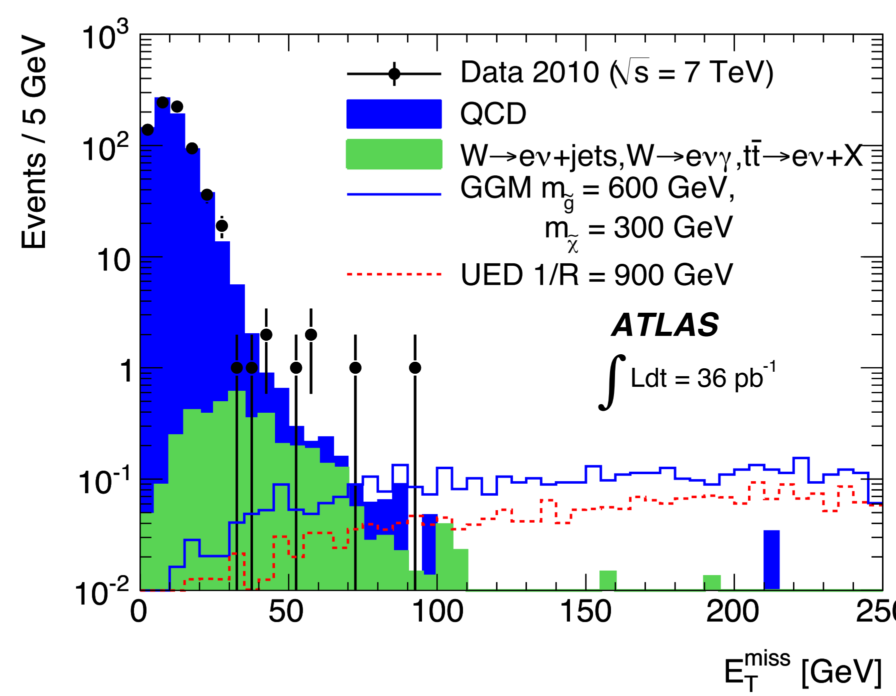
- ✓ gluino
- squark
  - ✓ 1st/2nd generation
  - sbottom
  - stop
- neutralino
  - bino
  - Higgsino (Z-rich)
  - Higgsino (h-rich)
  - wino
- slepton
  - flavor democratic
  - tau rich

Bino NLSP

- Bino NLSP occurs in Minimal Gauge Mediation, and gives rise to the most well-known GMSB signature: γγ+MET



- Latest search by CMS with 1.1/fb (SUS-11-009)
- Selection
  - >= 2 photons with pT>45, 30
  - >= 1 jet with pT>30
  - MET>100 GeV
- 0 events observed, 0.1±0.04 expected



Bino NLSP

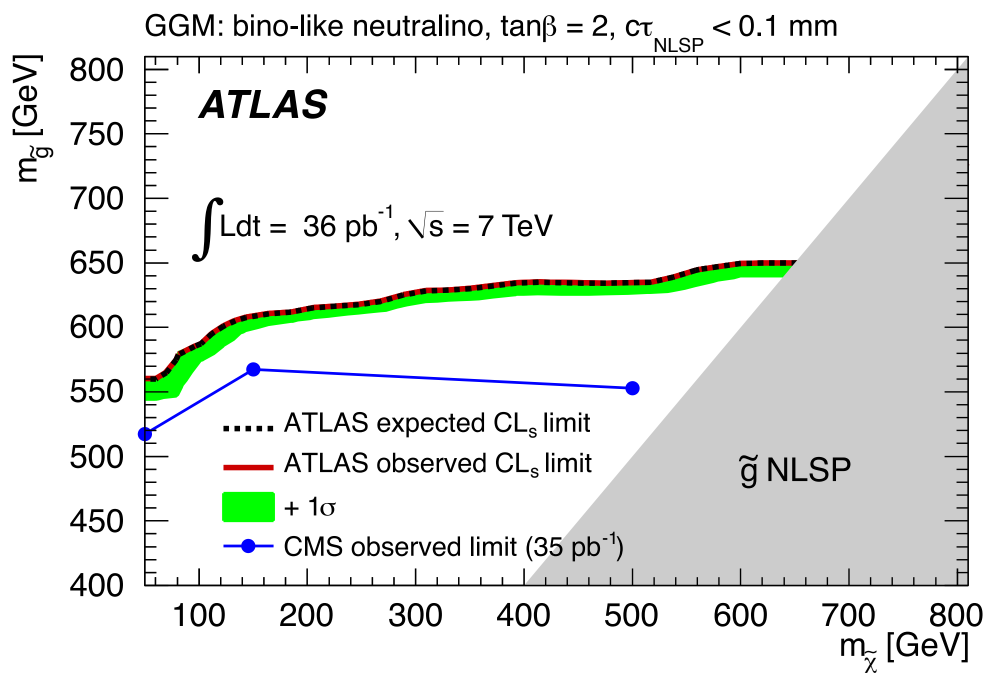
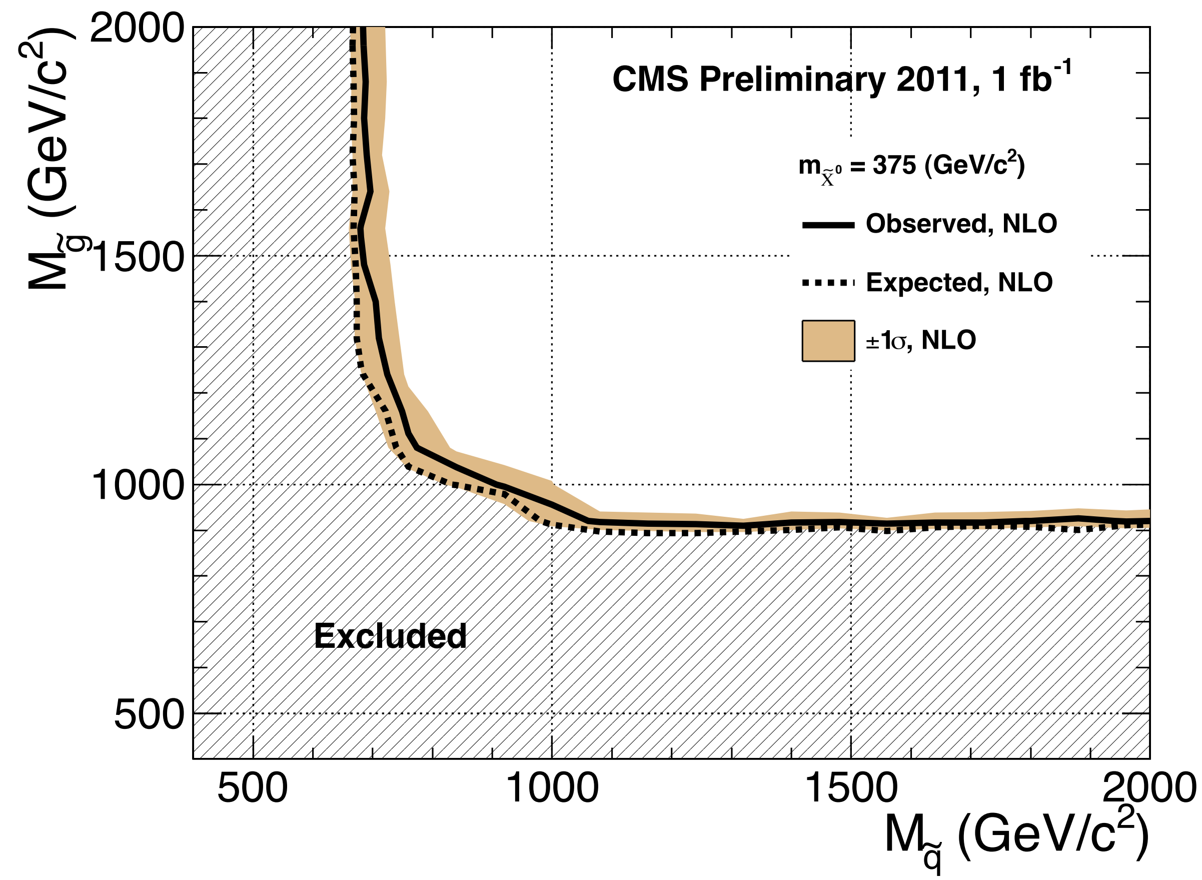


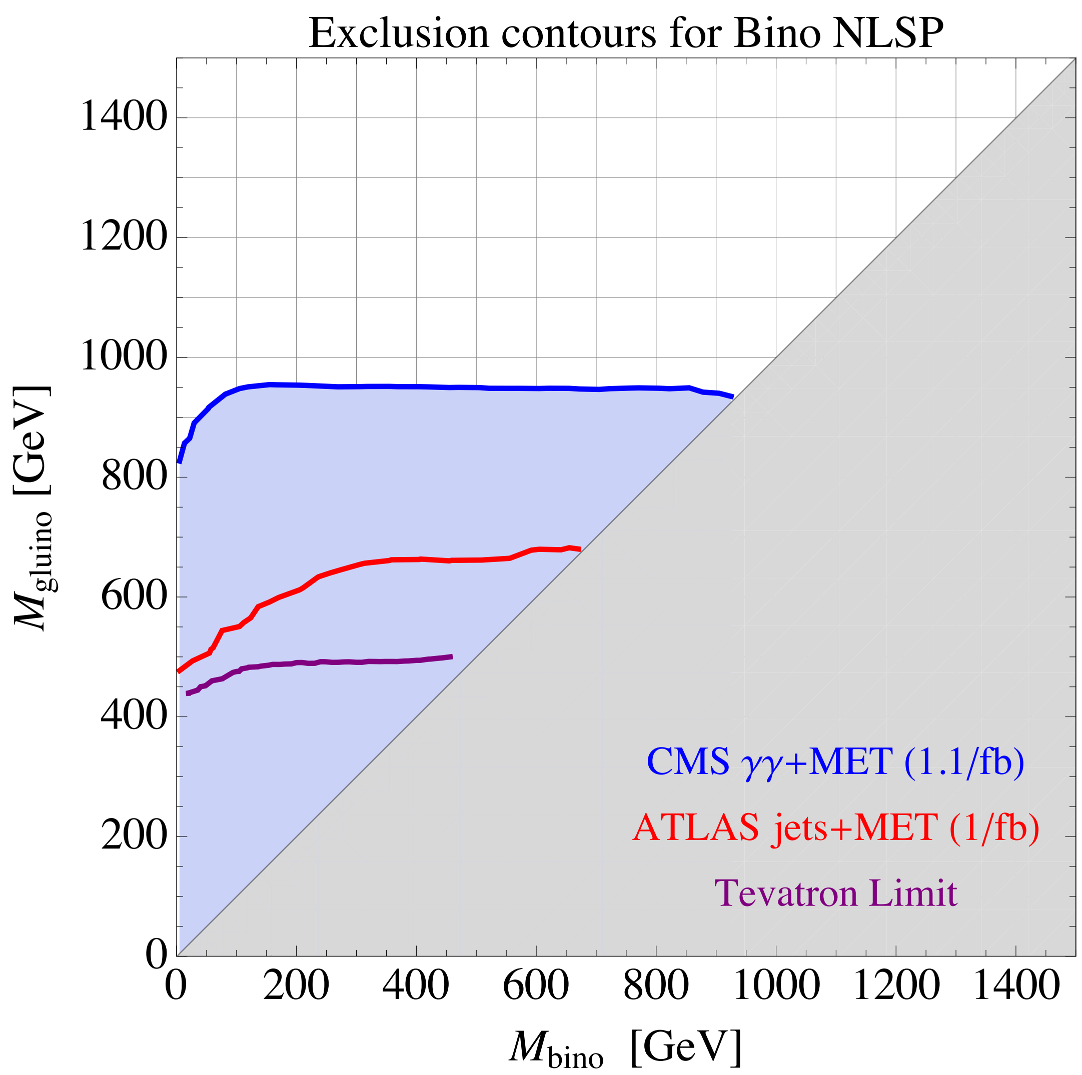
Fig. 5. Expected and observed 95 % CL lower limits on the gluino mass as a function of the neutralino mass in the GGM model with a bino-like lightest neutralino as NLSP (the grey area indicates the region where the NLSP is the gluino, which was not considered here). The other sparticle masses are fixed to $\sim 1.5\,\mathrm{TeV}$. Further model parameters are $\tan\beta = 2$ and $c\tau_{\mathrm{NLSP}} < 0.1\,\mathrm{mm}$. The observed limit and the -1σ expected error band are degenerate with the expected limit. CMS lower limits are from Ref. [26].

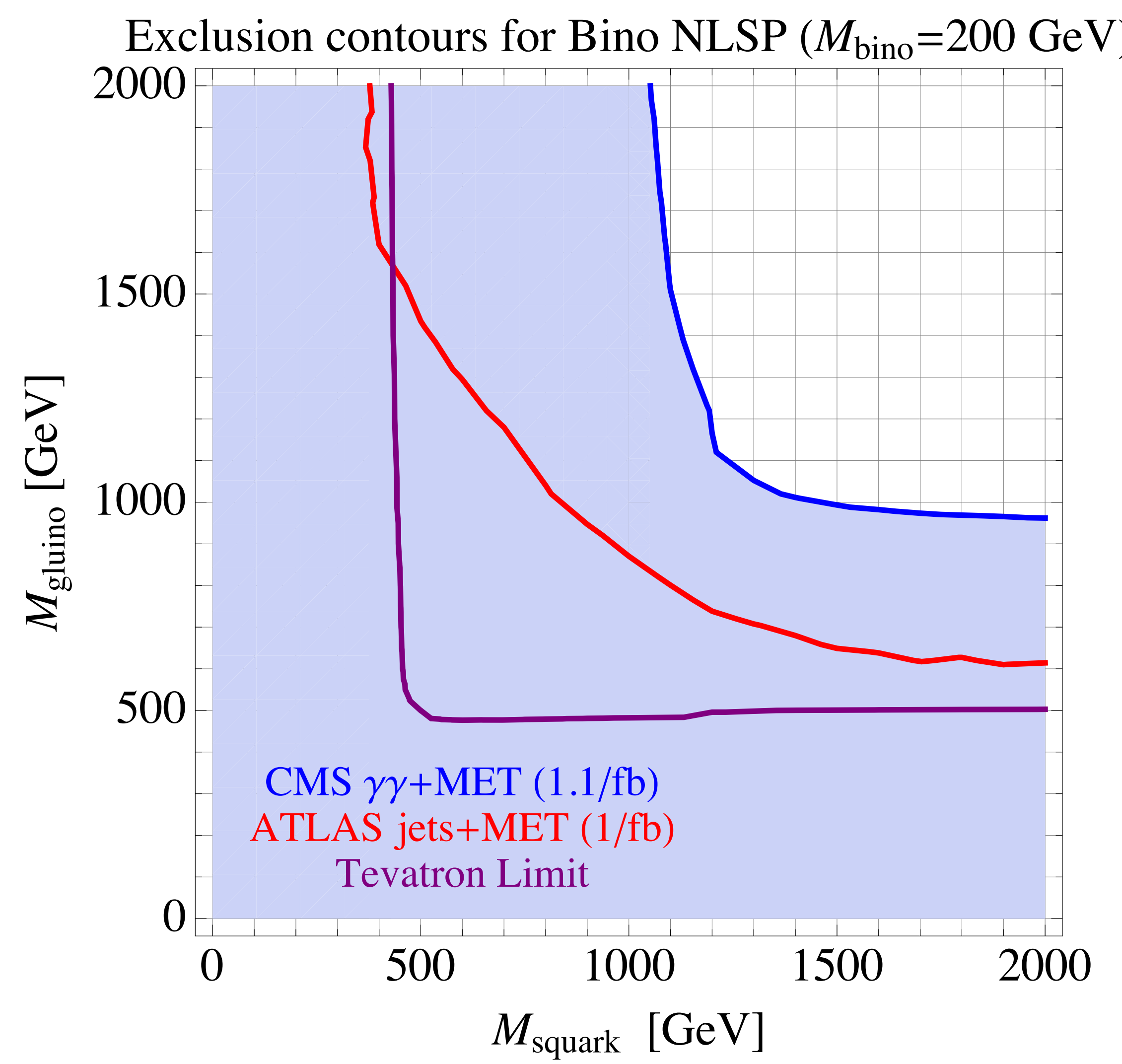


CMS and ATLAS are now expressing their results in GGM-motivated simplified parameter spaces! (Ruderman & DS)

How does this compare with jets+MET?

Bino NLSP





Not surprisingly, γγ+MET easily beats jets+MET, for Bino NLSP.

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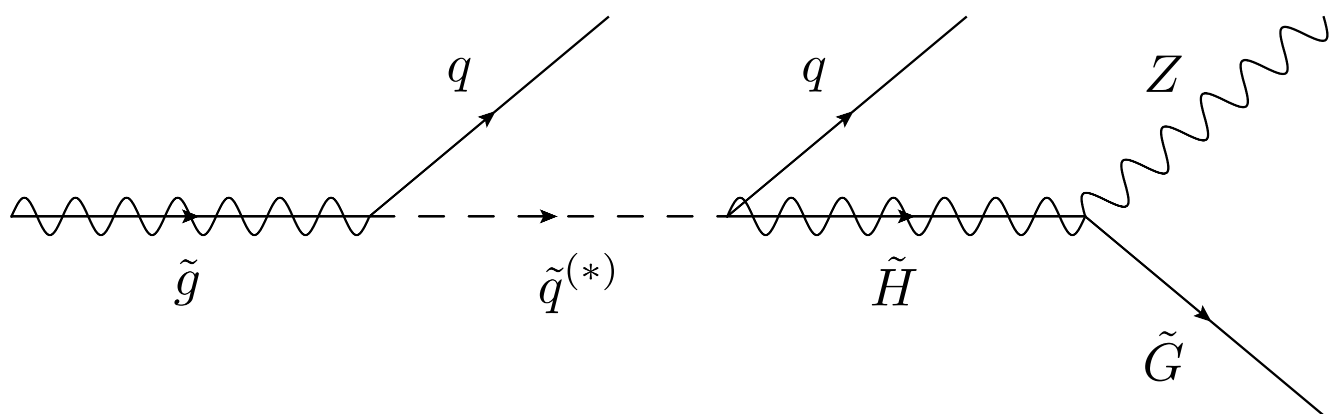
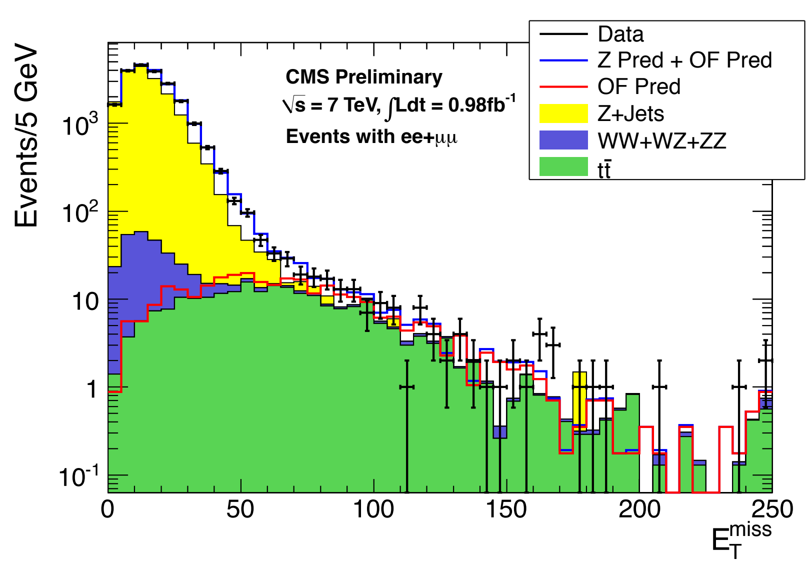
  - Higgsino (h-rich)
  - wino
- slepton
  - flavor democratic
  - tau rich

Z-rich Higgsino NLSPs

- If the NLSP is a Higgsino which decays primarily to Z's, Z(ll)+jets+MET is the ideal search channel.
(Matchev & Thomas; Meade, Reece & DS; Ruderman & DS)

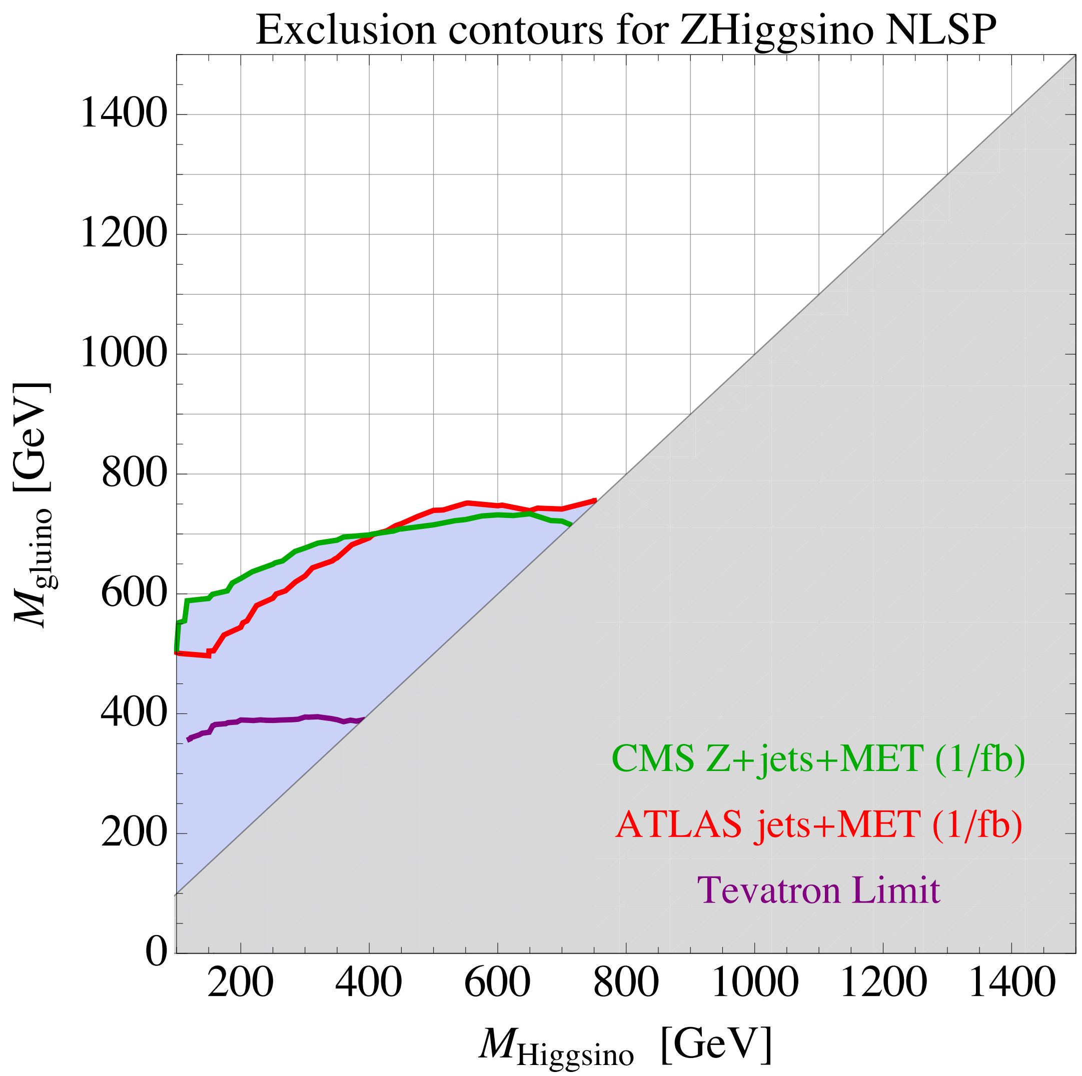


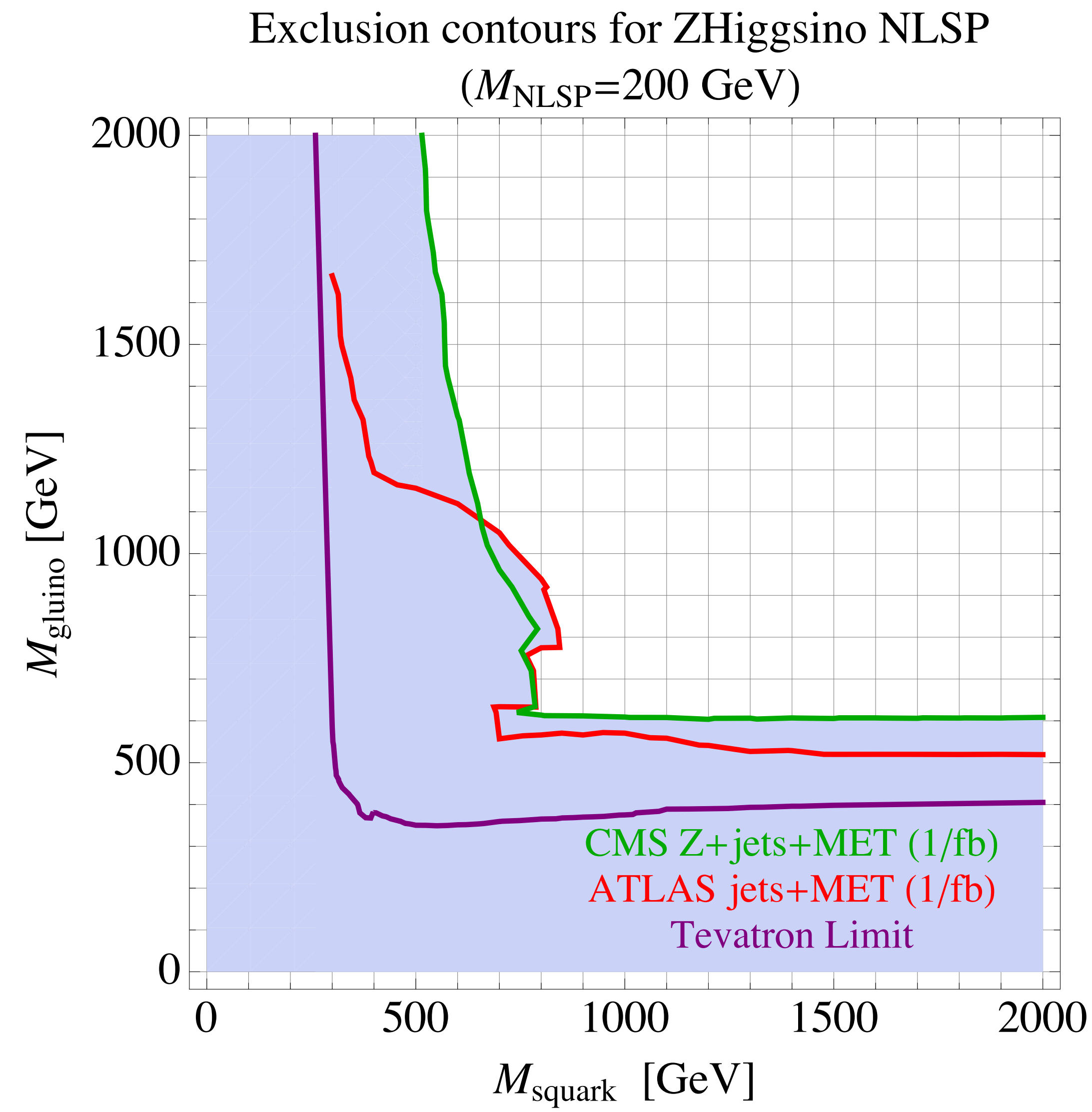
- Latest search by CMS with 0.98/fb (CMS-PAS-SUS-11-017)



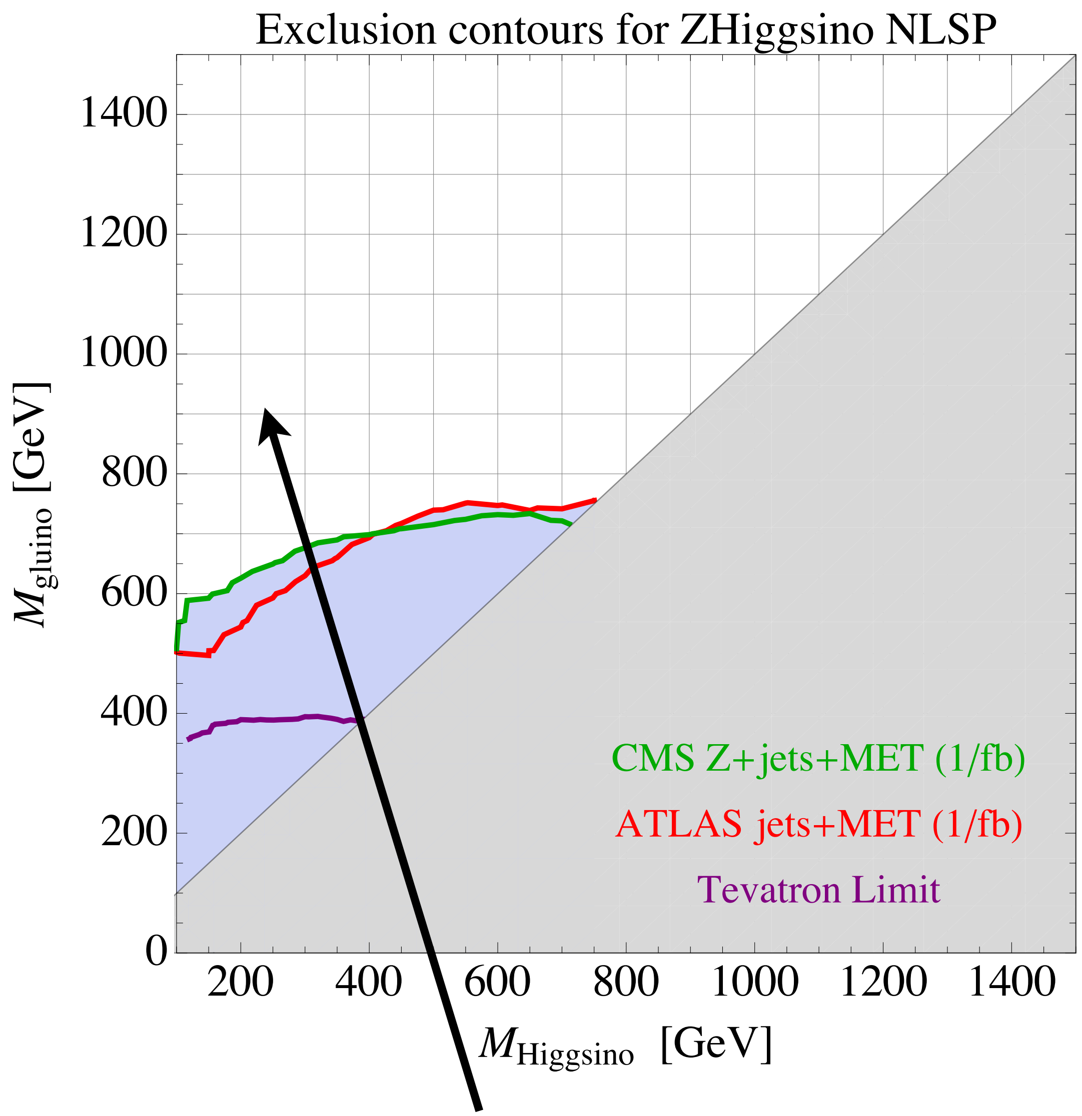
	$E_T^{miss} > 100$ GeV	$E_T^{miss} > 200$ GeV
Z Pred	$5.1 \pm 1.0 \pm 0.8$	$0.09 \pm 0.04 \pm 0.01$
$t\bar{t}$ Pred	$50.6 \pm 2.8 \pm 4.6$	$3.2 \pm 0.7 \pm 0.3$
Prediction	$55.7 \pm 3.0 \pm 4.6$	$3.3 \pm 0.7 \pm 0.3$
Data	**57 (25,32)**	**4 (1,3)**
UL	20	5.9

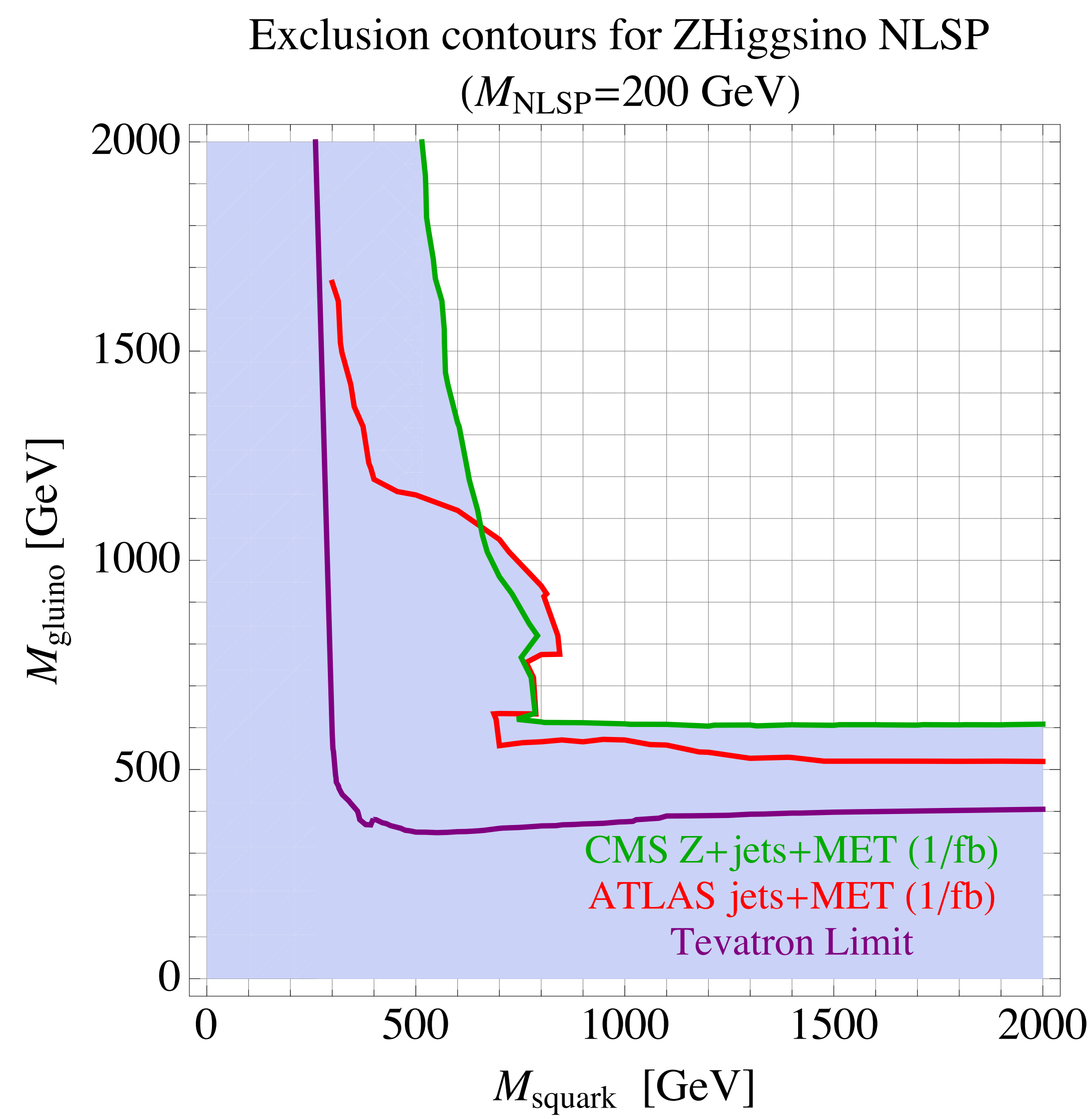
Z-rich Higgsino NLSP





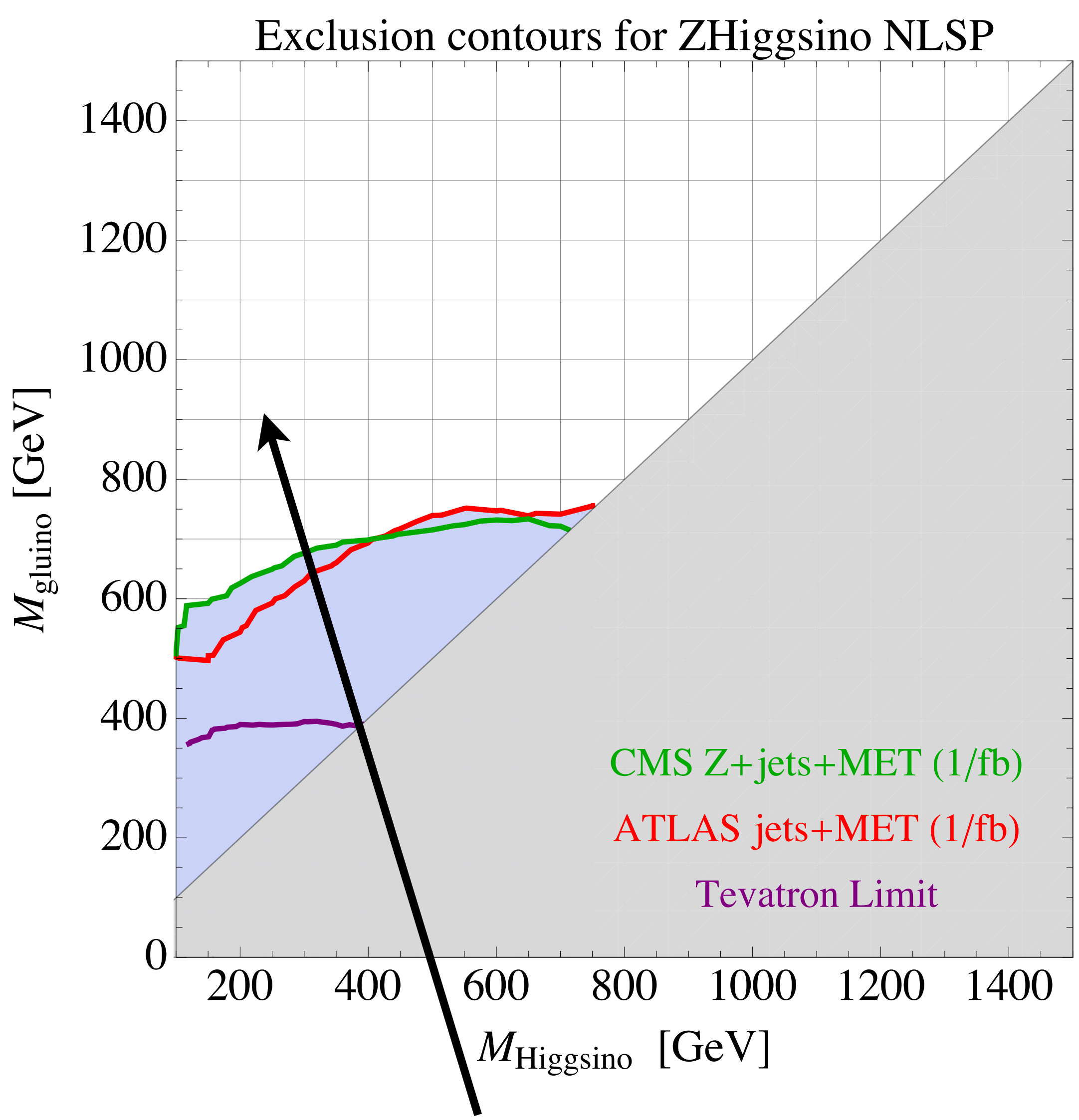
Z-rich Higgsino NLSP

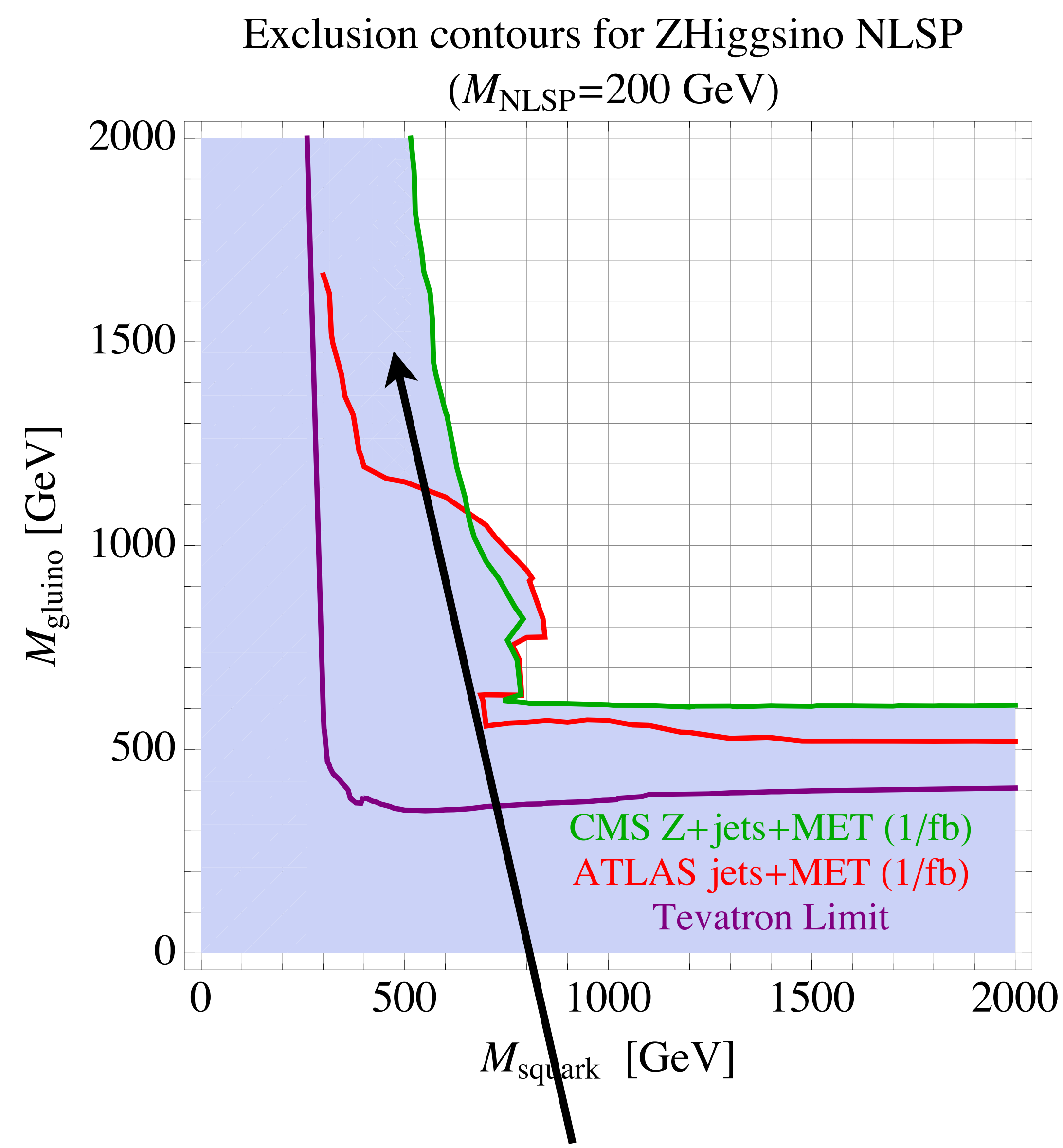




Cannot yet see direct Higgsino production.
Might need softer cuts plus more data.

Z-rich Higgsino NLSP





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Z+jets+MET is more robust than jets+MET,
since it is more inclusive for this NLSP type.

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  - Higgsino (h-rich)
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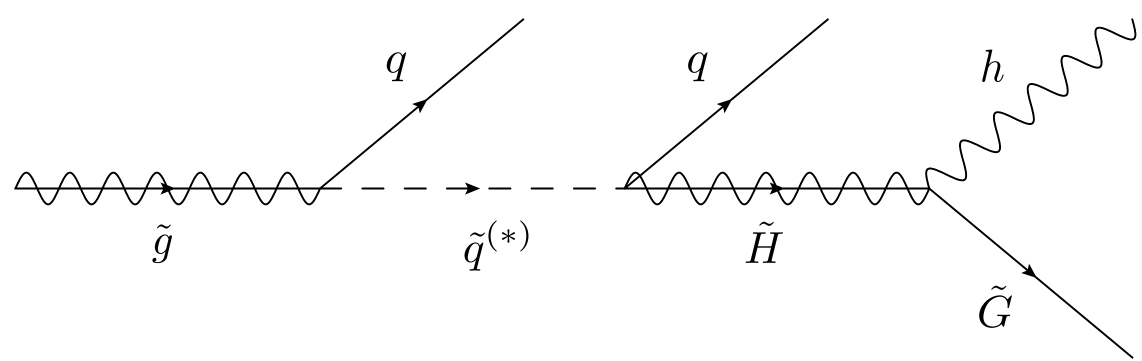
- slepton
  - flavor democratic
  - tau rich

h-rich Higgsino NLSP

- Higgsino NLSP can also decay primarily to h's. Then bjets+MET is a relevant final state.

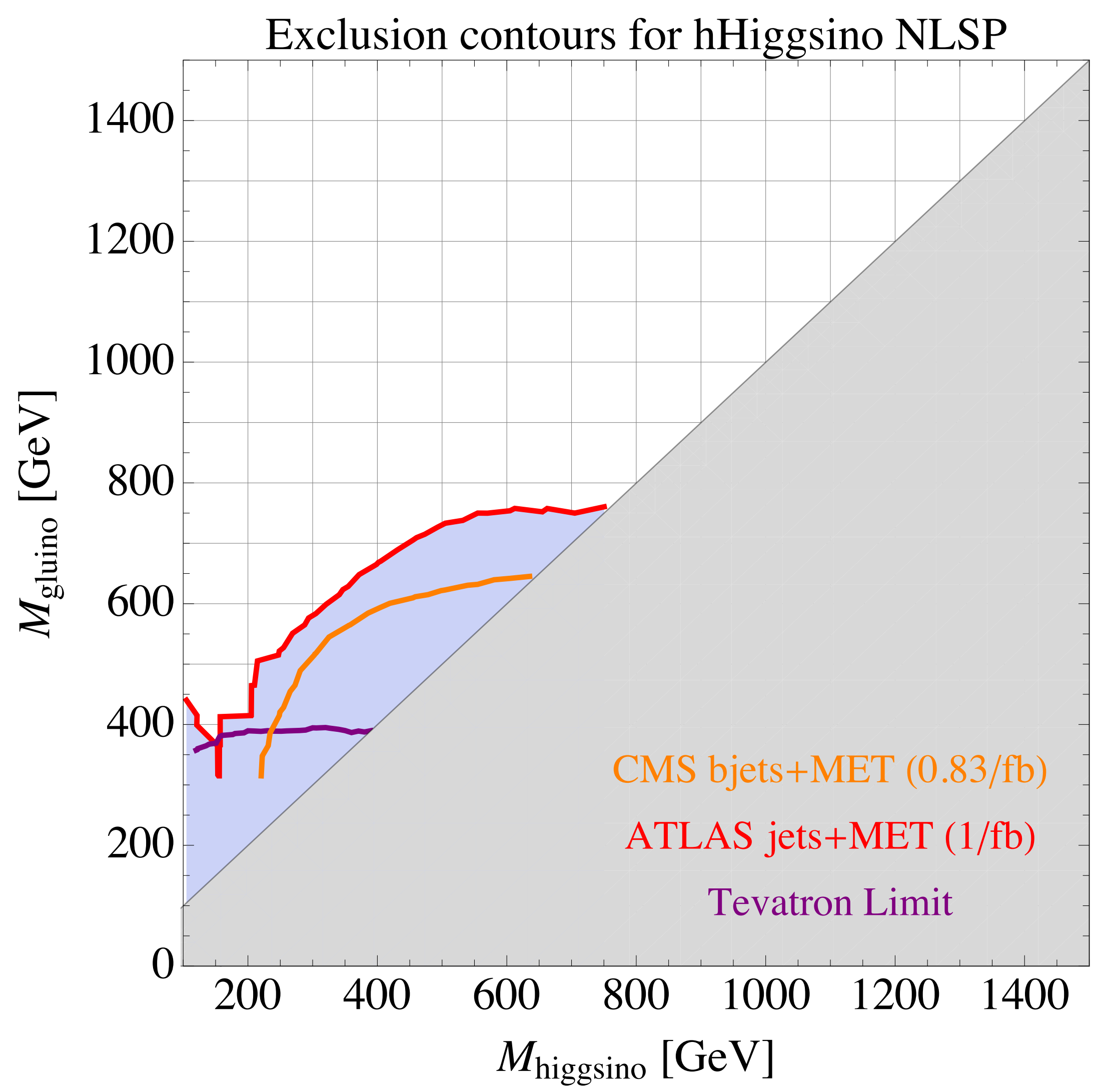


- Latest search by ATLAS with 0.83/fb (ATLAS-CONF-2011-098)

Sig. Reg.	Data (0.83 fb^{-1})	Top	W/Z	QCD	Total
3JA (1 btag m_{eff} >500 GeV)	361	221^{+82}_{-68}	121 ± 61	15 ± 7	356^{+103}_{-92}
3JB (1 btag m_{eff} >700 GeV)	63	37^{+15}_{-12}	31 ± 19	1.9 ± 0.9	70^{+24}_{-22}
3JC (2 btag m_{eff} >500 GeV)	76	55^{+25}_{-22}	20 ± 12	3.6 ± 1.8	79^{+28}_{-25}
3JD (2 btag m_{eff} >700 GeV)	12	$7.8^{+3.5}_{-2.9}$	5 ± 4	0.5 ± 0.3	$13.0^{+5.6}_{-5.2}$

Table 2: Summary observed and expected event yields in the four signal regions. The QCD prediction is based on the jet smearing method described in the text. Systematic uncertainties for the Standard Model predictions are given.

h-rich Higgsino NLSP



In this case jets+MET actually does better than the more specialized bjets+MET.

Mainly due to huge systematic errors in b-tagging. Will this be improved with more data?

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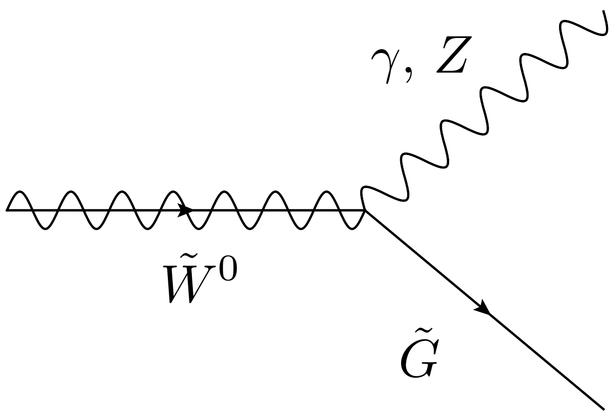
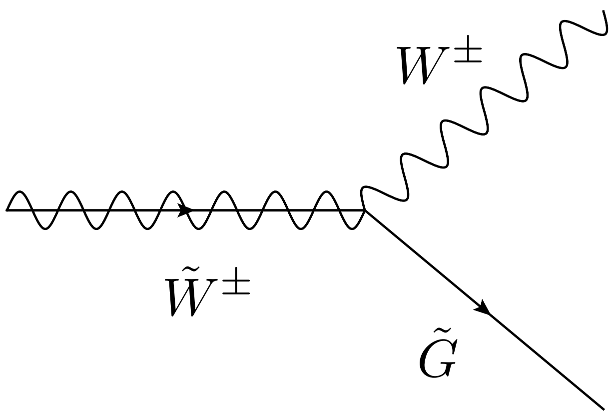
Wino co-NLSP

- Finally, for neutralino NLSPs, the last scenario is "Wino co-NLSP" (Meade, Reece & DS; Ruderman & DS)
- Here the co-NLSPs are a very degenerate wino-like chargino and neutralino.

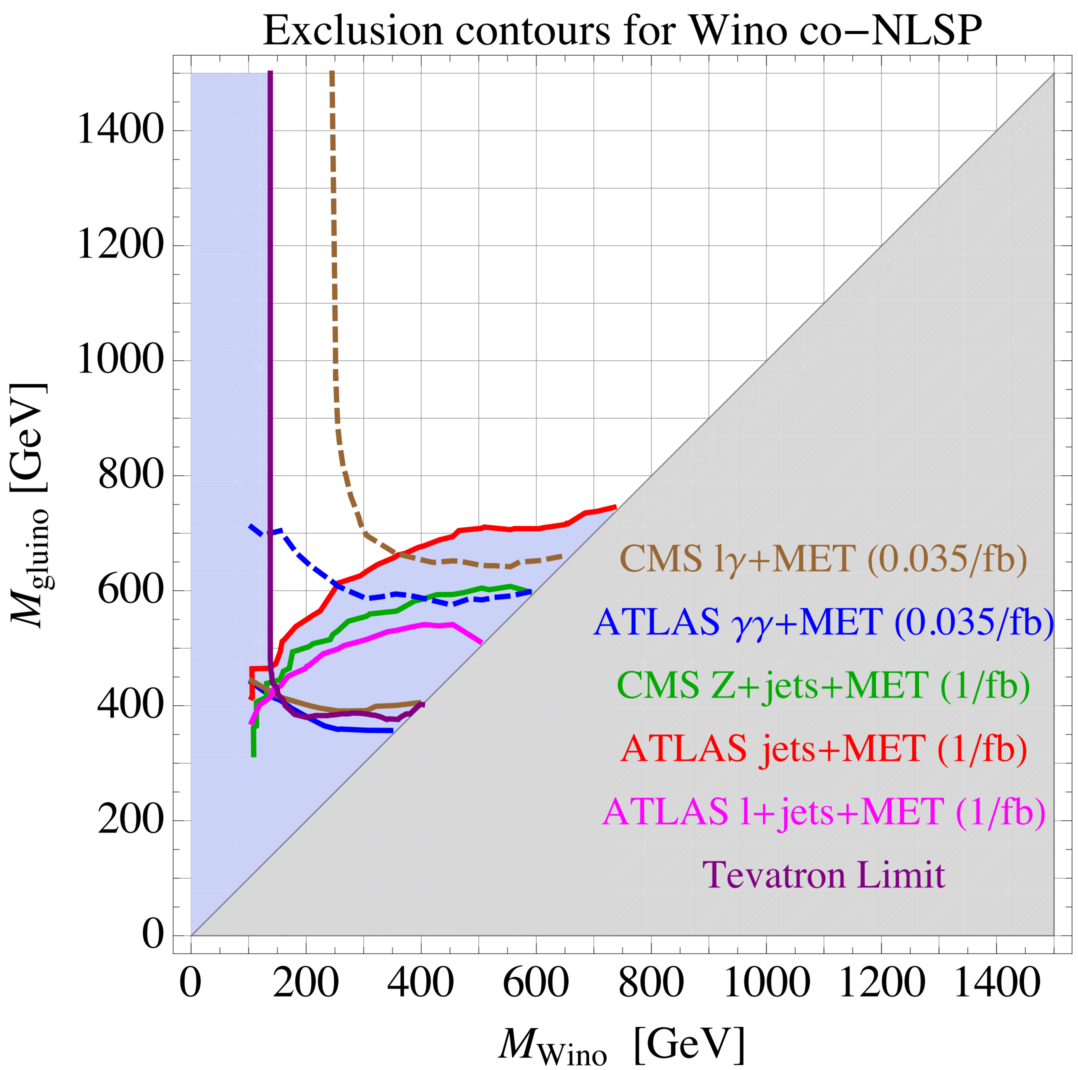


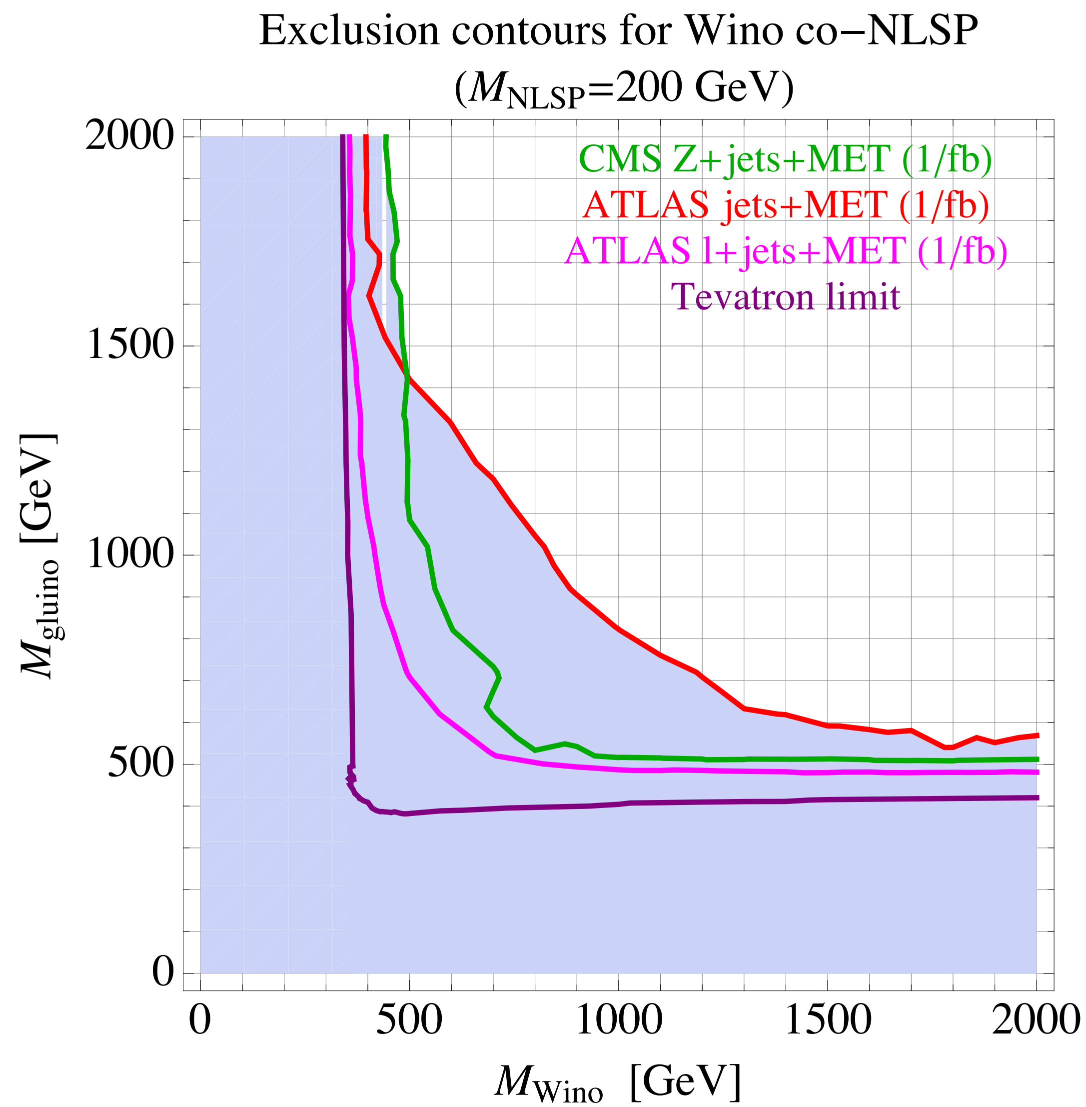


- Many interesting final states to consider!
  - jets+MET
  - l+jets+MET
  - Z+jets+MET
  - γ+l+MET
  - γγ+MET
  - γ+jets+MET

First dedicated analysis by CMS with 0.035/fb (1105.3152). (Initiated by discussions with Rutgers experimentalists!)

Wino co-NLSP





With 1/fb, lγ+MET could start to see direct wino production!

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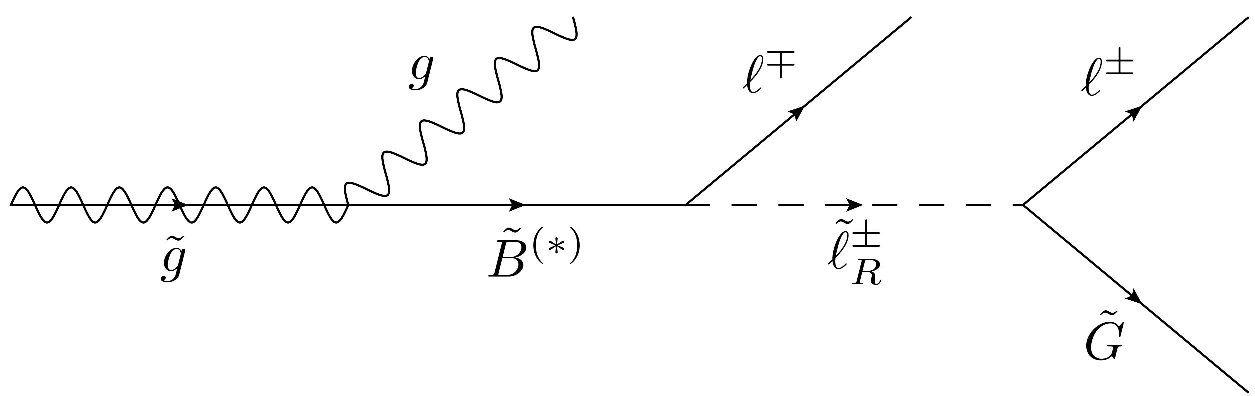
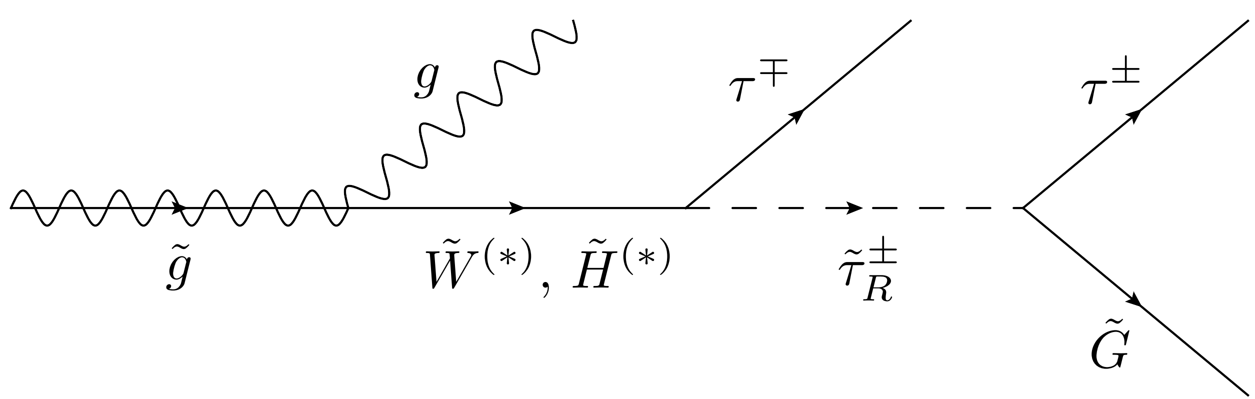
Slepton co-NLSP

- Finally, we come to the slepton (co-)NLSP scenario.



“flavor democratic”



“tau-rich”

- Here SS dileptons+MET and multileptons+MET can have amazing sensitivity (Ruderman & DS)

Slepton co-NLSP

- Latest SS dileptons search by CMS with 0.98/fb (CMS-PAS-SUS-11-010)

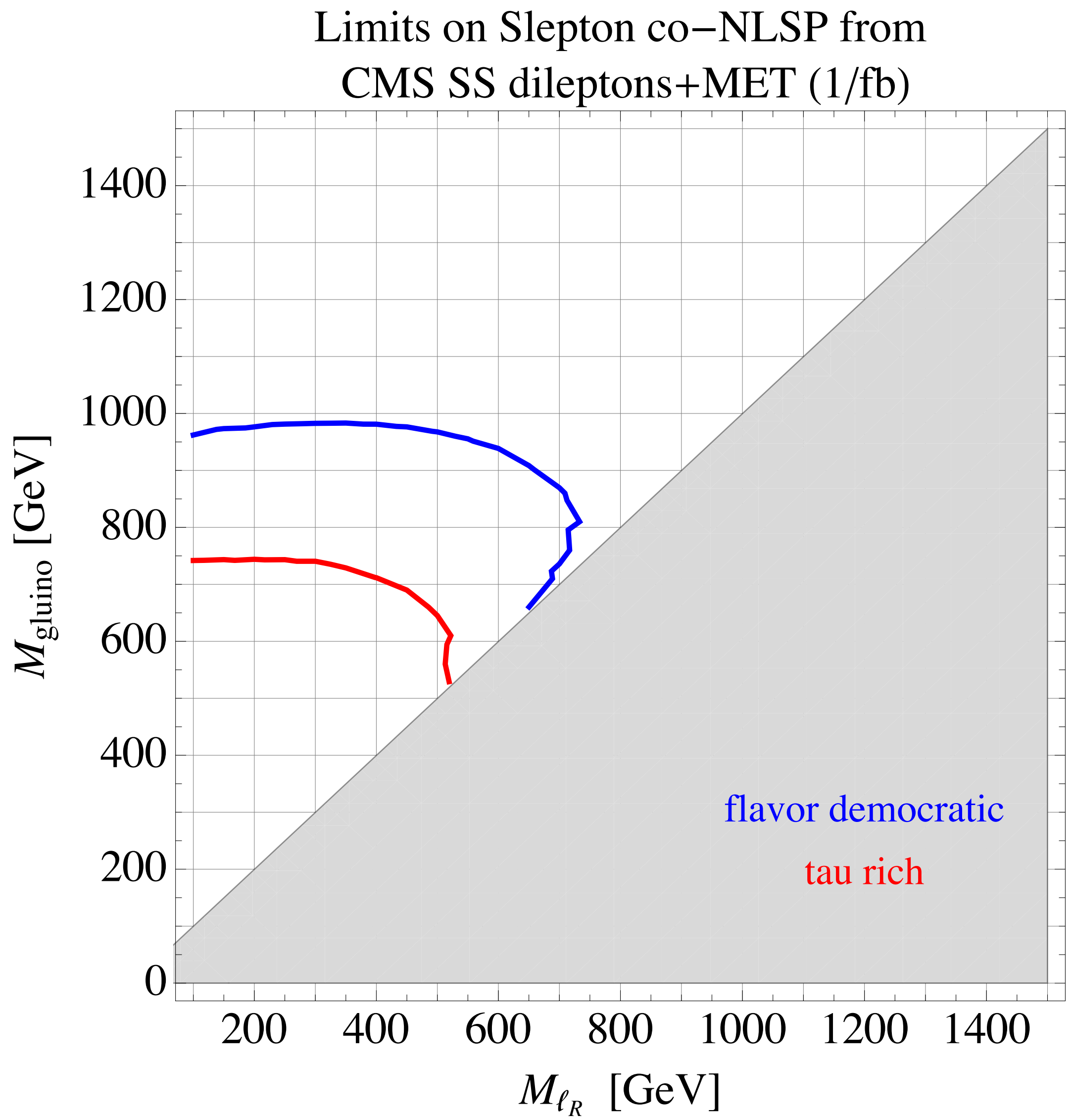
high pT baseline

Search Region (minimum H_T / E_T^{miss})	ee	$\mu\mu$	eμ	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background by (A1)	0.4 ± 0.3	0.4 ± 0.3	0.7 ± 0.4	1.4 ± 0.7	
Predicted background by (A2)	0.7 ± 0.5	0.4 ± 0.3	0.4 ± 0.3	1.4 ± 0.7	
Observed	0	0	0	0	3.0
Region 2 (400/50)					
Predicted background by (A1)	1.4 ± 0.8	1.3 ± 0.8	1.3 ± 0.6	4.0 ± 1.7	
Predicted background by (A2)	1.5 ± 0.8	0.8 ± 0.4	1.0 ± 0.5	3.3 ± 1.2	
Observed	1	2	2	5	7.5
Region 3 (200/120)					
Predicted background by (A1)	1.2 ± 0.7	1.5 ± 0.8	1.8 ± 0.8	4.5 ± 1.9	
Predicted background by (A2)	1.3 ± 0.7	1.8 ± 0.8	1.8 ± 0.7	4.9 ± 1.8	
Observed	0	2	1	3	5.2
Region 4 (80/100)					
Predicted background by (A1)	2.5 ± 1.2	2.6 ± 1.2	4.9 ± 2.2	10 ± 4	
Predicted background by (A2)	2.4 ± 1.0	3.6 ± 1.6	4.4 ± 1.6	10 ± 4	
Observed	3	2	2	7	6.0

tau baseline

Search Region (minimum H_T / E_T^{miss})	$e\tau$	$\mu\tau$	$\tau\tau$	Total	95% CL UL yield
Region 1 (400/120)					
Predicted background	1.1 ± 0.4	1.8 ± 1.4	0.0 ± 0.2	2.9 ± 1.7	
Observed	1	2	0	3	5.8

Slepton (co-)NLSP



Can check: limits are robust even with more squeezed spectra

Limit on flavor-democratic case extremely strong -- comparable to γγ+MET for Bino NLSP

Limits on tau-rich case are weaker

SS dileptons is a very clean and powerful channel!

(Would also be interesting to investigate bounds from multileptons+MET)

Our Checklist

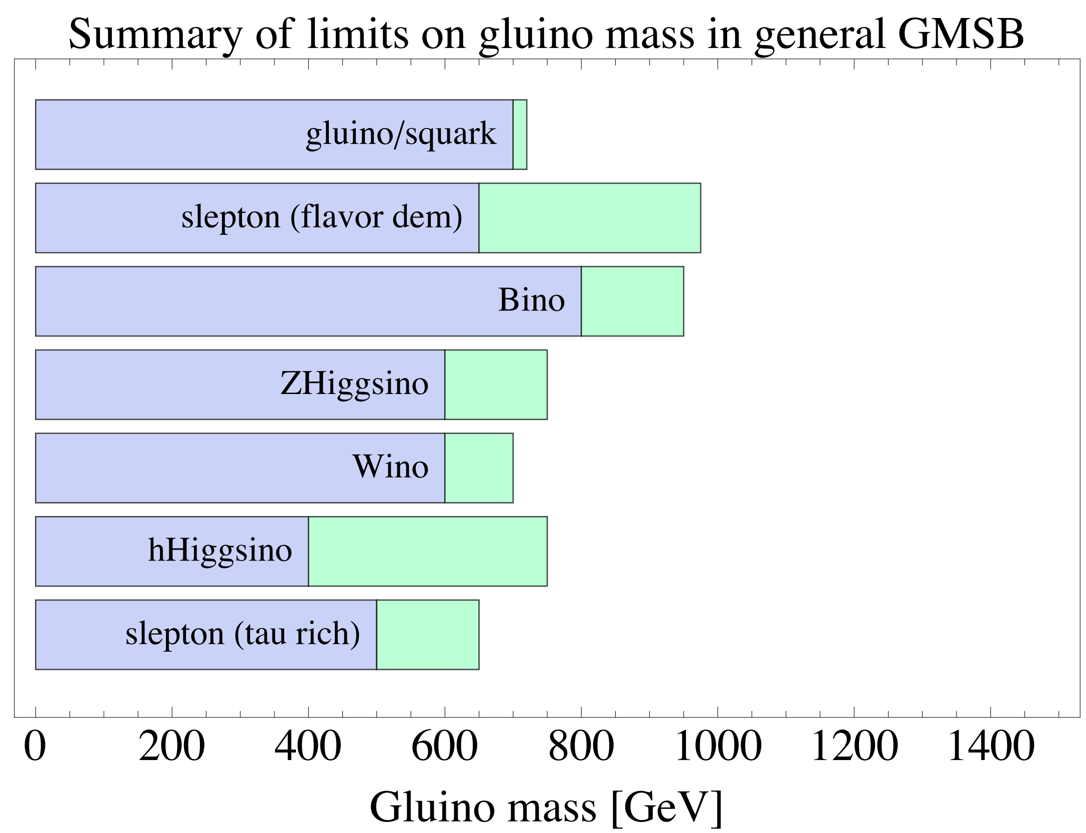
SUSY searches

- Hadronic:
  - ✓ jets+MET
  - ✓ b-jets+MET
- Leptons:
  - ✓ lepton+jets+MET
  - ✓ Z+jets+MET
  - ✓ SS dilepton+MET
  - multileptons+MET
- Photons:
  - ✓ diphoton+MET
  - ✓ lepton+photon+MET
  - photon+jets+MET

NLSP types

- ✓ gluino
- squark
  - ✓ 1st/2nd generation
  - sbottom
  - stop
- neutralino
  - ✓ bino
  - ✓ Higgsino (Z-rich)
  - ✓ Higgsino (h-rich)
  - ✓ wino
- slepton
  - ✓ flavor democratic
  - ✓ tau rich

Summary



- We have reviewed the current status of (most of) the LHC SUSY searches.
- GMSB with promptly decaying NLSPs is fairly well-covered. Generally, specalized searches for each NLSP type do better than jets+MET.
- Only moderate improvements over the Tevatron in several cases.
- Still no limits on EW production. Might need to optimize with softer cuts.

Future Directions

- Where the current searches are weakest:
  - 3rd generation (taus, bottoms, and tops)
  - Electroweak production
  - Longer decay chains, squeezed spectra
- We have not discussed:
  - Sbottom and stop NLSPs -- much weaker limits on direct production. Stop can even be lighter than the top! (Kats & Shih)
  - Scenarios with long-lived NLSPs (detector stable or displaced decays). Detector stable case well-covered; displaced decays are still unexplored (!)
  - Scenarios without MET such as R-parity violation

The End

Z+jets+MET

- Latest search by CMS with 0.98/fb (CMS-PAS-SUS-11-017)
- Selection:
  - e+e- or μ+μ- with pT>20 GeV and 81 GeV < m_{inv} <101 GeV
  - at least 2 jets with pT>30 GeV
  - MET > 100 GeV or MET > 200 GeV (two signal regions)
- Main backgrounds from Z+jets and ttbar.

bjets+MET

- Latest search by ATLAS with 0.83/fb (ATLAS-CONF-2011-098)
- Selection:
  - >= 1 jet with pT > 130 GeV, >= 2 additional jets with pT > 50 GeV
  - MET > 130 GeV
  - MET/M_{eff} > 0.25
  - $\Delta\phi_{min}$(jets,MET) > 0.4
  - 4 signal regions: 1 or 2 btags, M_{eff} > 500 or 700 GeV

SS dileptons

- Latest search by CMS with 0.98/fb (CMS-PAS-SUS-11-010)
- Selection:
  - At least one SS dilepton pair. pT(electron) > 10 GeV, pT(muon) > 5 GeV, pT (tau) > 15 GeV. Minv(dilepton) > 5 GeV.
  - At least two 2 jets with pT > 40 GeV
  - MET > 30 GeV
  - Z-veto with OS dilepton pairs
  - Three "baseline selections":
    - inclusive (HT>200, no tau)
    - high-pT (pT1>20, pT2>10, no tau)
    - tau (HT>350, MET>80, at least one tau)
  - Four "search regions":
    - HT>400, MET>120
    - HT>200, MET>120
    - HT>400, MET>50
    - HT>80, MET>100